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Requirements of a Coherent Laser Pulse-Doppler Radar*

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Summary—**The use of coherent detection can theoretically allow optical radar systems employing laser transmitters to achieve considerably improved receiver sensitivity, particularly in conditions of high background radiation. However, there are many practical factors that can limit sensitivity in coherent optical detection, which are described. It is shown that to achieve an efficient coherent optical radar, one would generally like a pulse width less than 10 μsec and a spectral line width less than 10 Mc.**

I. INTRODUCTION

THE DEVELOPMENT of the laser, which generates a coherent light signal, provides the potentiality of practical optical radar systems. One of the advantages of coherent light is that it allows the beam to be very narrow. However, an even more important advantage for the optical radar application is that it allows the receiver to employ coherent detection and thereby to achieve considerably greater sensitivity in daylight operation. The purpose of this paper is to describe the requirements and performance of coherent optical detection in an optical radar application, and to compare the performance with that achieved by noncoherent detection.

A photodetector acts as a square-law detector, providing an electrical output power proportional to the square of the input optical power. In a conventional optical receiver, the received optical signal is fed alone into the detector, and noncoherent detection is performed. In a coherent optical receiver, the received optical signal is summed with a coherent optical reference (called the local-oscillator reference) and the summed optical signal is fed to the photodetector. The squaring process of the detector effectively multiplies the received signal and the local-oscillator reference together, and the bandwidth narrowing of the subsequent amplifier effectively integrates the resultant product. This combination of multiplication and integration in coherent detection performs a cross correlation, which allows the receiver to achieve considerably greater sensitivity than one employing noncoherent detection.

If the local-oscillator reference is a pure sinusoid and its power can be made arbitrarily large, the effects of background optical power and dark current in the detector become negligible, and the optical receiver is able to achieve detection characteristics given by

$$\frac{P_{so}}{P_{no}} = \frac{QP_s}{(h\nu)\Delta f} \tag{1}$$

where (P_{so}/P_{no}) is the signal-to-noise power ratio out of the receiver, Δf is the receiver noise bandwidth, P_s is the received optical power, Q is the quantum efficiency of the detector, and $h\nu$ is the energy per photon (Planck's constant h times optical frequency ν).

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At present, there are two optical wavelengths which are of particular interest: 6943 Å for the ruby laser and 11,500 Å for the gas laser. At these wavelengths, the energy per photon is

$$h\nu = 2.85 \times 10^{-19} \text{ joules} \qquad \text{(Ruby, 6943 Å)}, \tag{2}$$

$$h\nu = 1.72 \times 10^{-19} \text{ joules} \qquad \text{(Gas, 11,500 Å)}. \tag{3}$$

It is desirable to compare the sensitivity of a coherent optical receiver to that of a microwave receiver. For a microwave radar the expression equivalent to (1) is

$$\frac{P_{so}}{P_{no}} = \frac{P_s}{KT_{\text{eff}}\Delta f} \tag{4}$$

where K is Boltzman's constant and T_{eff} is the effective noise temperature of the receiver. Thus, for unity quantum efficiency Q, the energy per photon $h\nu$ is equivalent to KT_{eff}. Setting $h\nu$ equal to KT_{eff} gives the following ideal noise temperatures for optical receivers:

$$T_{\text{eff}} = 20{,}800°\text{K} \qquad \text{(Ruby, 6943 Å)}, \tag{5}$$

$$T_{\text{eff}} = 11{,}500°\text{K} \qquad \text{(Gas, 11,500 Å)}. \tag{6}$$

Thus, even if ideal detection is achieved, an optical receiver is very noisy in comparison with microwave receivers.

On the other hand, quantum efficiencies of photodetectors are generally much less than unity. The best values achieved to date for photomissive surfaces at the wavelengths of the ruby and gas lasers are as follows:

$$Q = 0.04 \text{ for Type S20 Photosurface at 6943 Å}, \tag{7}$$

$$Q = 1.5 \times 10^{-4} \text{ for Type S1 Photosurface at 11,500 Å}. \tag{8}$$

The ideal noise temperatures given in (5) and (6) should be divided by these quantum efficiencies to obtain the noise temperatures now achievable with photoemissive detectors. Dividing these resultant effective noise temperatures by room temperature (291°K) gives the noise figures NF of the practical optical receivers, which are,

$$\text{NF} = 32.5 \text{ db (Ruby, 9643 Å)}, \tag{9}$$

$$\text{NF} = 54.5 \text{ db (Gas, 11,500 Å)}. \tag{10}$$

These are very high in comparison to microwave receivers. Semiconductor photodetectors promise quantum efficiencies close to unity, but now have too slow a speed of response to be generally desirable for a coherent laser receiver. This point will be discussed later.

To minimize the signal required to achieve a given signal-to-noise ratio at the receiver output, (1) shows that the receiver noise bandwidth Δf should be made as small as possible. However there are important effects that place a lower limit on the value of Δf, which are as follows:

1) Spread of spectral line due to pulsing,
2) Spread of spectral line due to lack of perfect coherence of the optical signal,
3) The effect of Doppler shift.

The most fundamental limitation is point 1). Points 2) and 3) are discussed later.

Fig. 1 shows the voltage spectrum of a signal at frequency F_0 modulated by a rectangular pulse of width τ. The pulse modulation smears the signal in frequency. In order to pass a reasonable amount of the pulse power, the receiver noise bandwidth Δf should be at least equal to $1/\tau$:

$$\Delta f \geqq 1/\tau. \tag{11}$$

To achieve maximum sensitivity, Δf should be equal to $1/\tau$. Set $\Delta f = 1/\tau$ in (1) and solve for P_s.

$$P_s \geq (P_{so}/P_{no})h\nu/Q\tau. \tag{12}$$

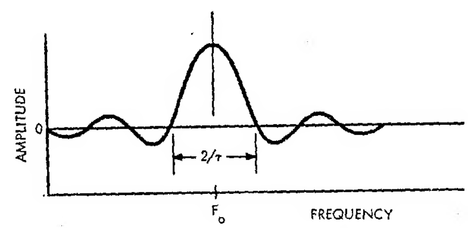

Fig. 1—Voltage spectrum of pulse-modulated signal of frequency F_0 and pulse width τ.

This equation is not strictly correct, because it ignores the loss of signal power through the filter. However, for the purpose of simplicity, this small discrepancy will be ignored. It can readily be accounted for by specifying a somewhat larger value for the output signal-to-noise ratio P_{so}/P_{no} at the threshold.

The received signal energy E_s is equal to $P_s\tau_s$ which by (12) is equal to the following for optimum detection:

$$E_s = (P_{so}/P_{no})(h\nu)/Q. \tag{13}$$

If Q could be made unity, (13) shows that the number of photons (of energy $h\nu$) required for detection is ideally equal to the signal-to-noise power ratio (P_{so}/P_{no}) required at the threshold. Since the signal-to-noise ratio at the threshold must be at least 10 db, the system must receive at least 10 photons in order to achieve a reasonably high probability of false alarm and low probability of false dismissal, for an ideal detector. With a practical photoemissive detector available today ($Q = 0.04$) the system must receive at least 250 photons at the ruby laser frequency.

If noncoherent detection is employed, the signal power that can be detected is given by the following:

$$P_{s(nc)} = \sqrt{2P_n P_{s(c)}}, \tag{14}$$

where

P_n = effective optical noise power on detector,
$P_{s(c)}$ = signal power detectable by coherent detection,
$P_{s(nc)}$ = signal power detectable by noncoherent detection.

The noise power P_n represents the power in the background radiation that falls on the detector plus the effect of the detector dark current in terms of the equivalent optical power. The loss $L_{(nc)}$ produced by noncoherent detection is

$$L_{(nc)} = \frac{P_{s(nc)}}{P_{s(c)}} = \sqrt{\frac{2P_n}{P_{s(c)}}} = \sqrt{\frac{2P_n\tau}{E_{s(c)}}} \qquad (15)$$

where $E_{s(c)}$ is the signal energy required for coherent detection, which was given in (13).

Eq. (15) shows that in order to minimize the loss when noncoherent detection is performed, one should 1) make the pulse length τ as short as possible and 2) make the optical noise P_n as small as possible. The dark current component of noise power can be kept small by cooling the detector in liquid nitrogen. If the detector operates at night, the background optical power can be kept small. If the pulse is made very short, the loss with noncoherent detection under such conditions is small. However, under daylight conditions, there is considerable loss in sensitivity with noncoherent detection.

When noncoherent detection is performed, the dark current of the photodetector is very important. However, with coherent detection, the dark current can be ignored as long as its effective power is small in comparison to the local-oscillator power. With coherent detection, the quantum efficiency is the parameter that is of primary importance. It may well be that better photosurfaces can be achieved in coherent-detection optical receivers by sacrificing low dark current to achieve higher quantum efficiency.

II. Laser Radar Design

Let us now consider what is required in terms of equipment and equipment performance to realize an effective coherent laser radar.

Fig. 2 gives a block diagram of a coherent laser radar. A CW laser oscillator 1) generates a signal at optical frequency F_o. This is fed to a pulse-modulated amplifier 2) which generates a pulsed optical signal of carrier frequency F_o. The target echo frequency is shifted from the transmitted frequency F_o by the Doppler shift F_d, and so has a carrier frequency of (F_o+F_d). An optical frequency translator 3) is often needed to shift the local-oscillator frequency from the frequency F_o of the CW laser oscillator by an offset frequency F_x. Thus the local-oscillator signal has a frequency of (F_o+F_x). The local oscillator signal and target echo signal are summed together optically 4) and fed to the photodetector 5). The photodetector gives as an output a signal at the difference between the target echo frequency (F_o+F_d) and the local-oscillator frequency (F_o+F_x), which is thus at the frequency $|F_d-F_x|$. This signal is fed to the receiver.

The target Doppler frequency shift F_d is given by the following expression:

$$F_d = 2V/\lambda \qquad (16)$$

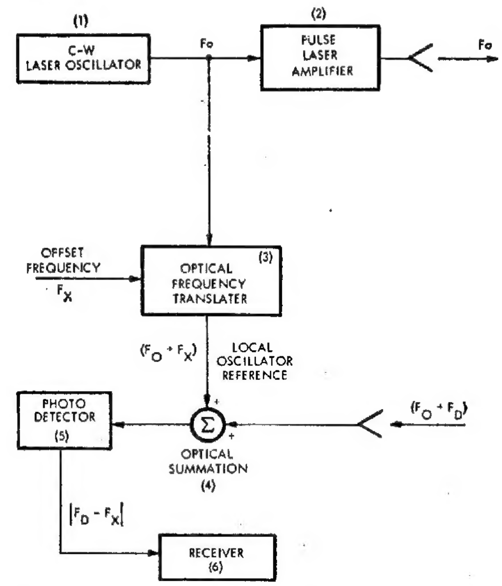

Fig. 2—Block diagram of a coherent optical radar.

where V is the relative closing velocity and λ is the wavelength of the optical signal. For the ruby laser wavelength 6943 Å, the Doppler shift is 875 kc/ft/sec (or in round numbers 1 Mc/ft/sec).

It appears that laser radar systems may be quite useful in space vehicle applications. Relative velocities for such applications may be as high as 10 miles per sec, which represents the relative speed between two low-altitude satellites traveling in opposite directions. The Doppler shift at the ruby laser wavelength for this extreme condition is 50 Gc. Thus for space vehicle applications a coherent laser radar would have to operate over frequencies from 0 to 50 Gc.

If a frequency translator were not used, the photodetector would have to pass the Doppler frequency which could be as high as 50 Gc for a space vehicle application. By using a frequency translator, the photodetector need merely pass the difference between the Doppler frequency F_d and the offset frequency F_x, which can be relatively small.

The most convenient detector available today is the photomultiplier tube. Commercial units are capable of passing 300 Mc, but much wider bandwidths appear to be possible. Another approach is the TWT phototube, which now can pass frequencies from 2 to 4 Gc. Semiconductor photodetectors promise much higher quantum efficiencies but appear to be limited to much lower bandwidths.

Although the frequency translators allow the detector to operate with a bandwidth much less than the Doppler shift, it is usually desirable that the detector have the widest possible bandwidth in order that it can simultaneously examine the largest possible region of Doppler frequencies during search.

The receiver that follows the photodetector will generally have a large number of parallel frequency channels to allow it to achieve a relatively narrow receiver

noise bandwidth Δf yet also be able to cover the full Doppler frequency region passed by the photodetector. The narrower the noise bandwidth Δf, the greater number of channels are required. Therefore, practical considerations place a lower limit on the allowable filter bandwidth.

It appears that the receiver bandwidth Δf may typically be between 1 Mc and 100 Mc. Since 1 Mc corresponds to a speed resolution of 1 ft/sec, a bandwidth below 1 Mc would lead to very difficult tracking problems, and would require an excessive number of receiver channels during search. With a 10-Mc bandwidth, 30 filters would be required to cover the 300-Mc region of the photodetector, which appears reasonable. With an TWT phototube, which has a 2000-Mc bandwidth, a wider filter bandwidth may be desirable. On the other hand, if the radar is used for ground tracking applications, where Doppler shifts are small, a bandwidth of 1 Mc might be used.

We will thus assume a receiver bandwidth Δf of 10 Mc as a typical number. To achieve optimum detection, the pulse width τ should be equal to $1/\Delta f$ or 0.1 μsec. Such a laser radar system would achieve a speed resolution of 11 ft/sec and a range resolution of 50 ft. It also would have very high angular resolution. Thus a laser radar is capable of achieving very high resolution in speed, range and angle. In contrast, a microwave radar has relatively poor angular resolution; and can achieve range resolution without speed resolution (in a pulse radar), or speed resolution without range resolution (in a Doppler radar).

The laser radar has much greater resolution capability than a microwave radar, but is far inferior in search. The poor search capability is due to 1) its high noise figure, 2) the generally smaller capture area of its receive aperture, 3) the low efficiency of lasers. For this reason laser radars will probably usually be operated in conjunction with other equipment (often microwave radar), which will perform the coarse search function. The laser radar will generally search over only a relatively small region of range, speed, and angle.

It has been shown that we would like to operate with a receiver bandwidth Δf of the order of 10 Mc with a pulse width τ of 0.1 μsec. This gives the optimum detection condition $\tau\Delta f=1$. However, as will be shown we can tolerate without excessive degradation a value of $\tau\Delta f$ up to 100, which would allow a 10-μsec pulse width for a 10-Mc bandwidth. Let us now examine the capabilities of present lasers to satisfy these requirements.

A serious problem of lasers is that they tend to oscillate in a number of modes to deliver a series of frequencies which are separate by the resonant frequency of the cavity, which is typically about 1.7 Gc. In order for efficient coherent detection to be performed, the CW laser oscillator and pulsed laser amplifier must be able to oscillate in a single mode. It is desirable that the line width be less than 10 Mc, although a somewhat wider width can probably be tolerated.

The gas laser is able to oscillate in a single mode in a CW fashion, but is not capable of generating short pulses of high peak powers. Thus it cannot now satisfy our requirement of a pulse length shorter than 10 μsec.

In contrast, the ruby laser can generate short pulses of high peak powers, but is very bad from a multimode point of view. It also tends to generate very erratic pulse trains, and does not oscillate readily in a CW fashion (which is needed to satisfy the CW oscillator requirements). Unfortunately gas and ruby lasers cannot be used together in a system because they operate at different optical wavelengths.

Thus there are many practical problems in laser design that must be solved before the coherent laser radar system can be realized. However, the purpose of this paper is to concentrate on the requirements of such a system and not the means of designing a laser to satisfy these requirements.

III. General Discussion of Coherent Detection

A detailed analysis of coherent and noncoherent detection in a photodetector is given in Section IV. This section presents a simplified analysis of the difference between coherent and noncoherent detection, and summarizes the performance achievable by coherent detection.

A. Simplified Analysis of Coherent and Noncoherent Detection

In a noncoherent detector, the signal is fed into a rectifying device. Since this device has no negative output, its response can be expressed as an even infinite series, as follows

$$e_o = ae_i^2 + be_i^4 + ce_i^6 + \cdots. \tag{17}$$

Generally one can ignore the higher order terms and get a good approximation of the action by assuming that $e_o = ae_i^2$, *i.e.*, that the rectifier is a square-law detector. A photodetector is an ideal square law device in which the higher terms of (17) are not present.

In a square-law detector, the output signal-plus-noise (s_o+n_o) is related as follows to the input signal-plus-noise (s_i+n_i):

$$s_o + n_o = a(s_i + n_i)^2 = a(s_i^2 + 2s_in_i + n_i^2) \tag{18}$$

where a is a constant, the output signal is (s_i^2), and the output noise is $(2s_in_i+n_i^2)$. The noise consists of two terms: one (n_i^2) due to beats between the noise components, and the other $2s_in_i$ due to beats between the signal and noise. If the input signal-to-noise ratio is much less than unity, n_i^2 is much greater than $2s_in_i$, and so the output noise and signal are approximately

$$s_o = as_i^2, \tag{19}$$

$$n_o \cong an_i^2 \quad \text{for} \quad (P_{si}/P_{ni}) \ll 1. \tag{20}$$

It can readily be seen that the output signal-to-noise ratio for this condition is

$$P_{so}/P_{no} \cong (P_{si}/P_{ni})^2. \quad (21)$$

Now consider coherent detection. The same detection device can be used. The important difference is that prior to the detector a coherent reference (or local-oscillator signal) is added to the input signal, the reference being much larger than the input signal or noise. Designate this reference as r. The total voltage into the detector is

$$e_i = (s_i + n_i + r). \quad (22)$$

For a simple square-law detector, the output voltage is

$$e_o = ae_i^2 = 2ar(s_i + n_i) + a(s_i + n_i)^2 + ar^2. \quad (23)$$

If $r \gg (s_i + n_i)$, the second term is negligible in comparison to the first and so can be ignored. If the reference is a pure sinusoid, the quantity ar^2 is a constant and so is generally of no concern. Thus the output can be expressed as

$$e_o = 2ar(s_i + n_i). \quad (24)$$

The reference thus beats with the signal and noise, and converts the signal spectrum down to a lower frequency, which is the difference between the two signals. This represents coherent detection. The coherence is not achieved by the detector itself, but rather by the addition of the reference with the signal prior to the detector. Because of this addition, correlation is actually performed within the detector, and this correlating process provides the improvement in detectability achieved by coherent detection.

With coherent detection, the output signal-to-noise ratio is equal to the input signal-to-noise ratio:

$$P_{so}/P_{no} = P_{si}/P_{ni}. \quad (25)$$

Dividing (25) by (21) gives the loss caused by noncoherent detection, which is

$$L_{nc} = (P_{si}/P_{ni})^{-1}, \qquad \text{for } P_{si}/P_{ni} < 1. \quad (26)$$

If the signal-to-noise ratio into the detector is greater than unity, there is little loss if noncoherent detection is used. However if the signal-to-noise ratio into the detector is much less than unity, the loss with noncoherent detection is high, being equal to the reciprocal of the input signal-to-noise ratio.

It has been assumed that the reference is a pure sinusoid. However, in a practical case it may contain noise itself. If the reference is much larger than other noise sources, the noise in the reference signal can be quite important. Express the reference as a sum of pure reference sinusoid r_0 plus a much smaller reference noise r_n:

$$r = r_o + r_n. \quad (27)$$

The component ar^2 which was neglected in (23) is equal to

$$ar^2 = a(r_o + r_2)^2 = ar_o^2 + 2ar_or_n + ar_n^2. \quad (28)$$

The first term is a constant and so is of no concern. The third term is negligible. Accordingly ignore these two terms and add the second term to (24). This gives

$$e_o = 2ar_o(s_i + n_i + r_n) \quad (29)$$

where r is replaced by r_o, since $r_n \ll r_o$. Thus the noise r_n in the reference adds directly to the input noise.

To reduce the effect of noise in the local-oscillator signal, a balanced detector is often used. The response of a balanced detector is given by

$$e_o = \frac{a}{2}\left[(s_i + n_i + r)^2 - K(s_i + n_i - r)^2\right] \quad (30)$$

where the constant K is made as closely as possible to unity. A balanced detector basically consists of two nearly identical detectors. Into one detector is fed the input plus the reference and into the other is fed the input minus the reference. The outputs from the detectors are subtracted to form the resultant signal. Multiplying out (30) gives

$$e_o = \frac{a}{2}\left[2r(s_i + n_i)(1 + K) + (1 - K)\left[(s_i + n_i)^2 + r^2\right]\right]. \quad (31)$$

If K is nearly equal to unity, and $r_o \gg (s_i + n_i)$, r_n, the output can be approximated quite well as

$$e_o = 2ar_o\left[(s_i + n_i) + \left(\frac{1 - K}{2}\right)r_n\right]. \quad (32)$$

Thus the balanced mixer reduces the magnitude of the reference noise voltage by the ratio $(1-K)/2$.

A balanced microwave mixer will typically reduce the effect of local-oscillator reference noise by the order of 30 db. It remains to be seen whether balanced mixers can be effective at optical frequencies.

B. Post-Detection Integration

Even though the coherent laser radar performs coherent detection in the photodetector, it may also perform noncoherent detection later in the receiver. This is because it may not be practical to adjust the pulse width τ to be equal to the reciprocal of the noise bandwidth Δf of the receiver. A much longer pulse width may be required, and the receiver cannot by itself provide adequate integration.

In this case, the electrical signal from each channel of the amplifier is fed through a rectifier (which acts as a noncoherent detector) and then to a low-pass filter of time constant, roughly equal to the width of the pulse. This low-pass filter integrates the signal and thereby further reduces the noise.

The signal ou[illegible] threshold device. To achieve high probability of detection and low probability of false alarm, the signal-to-noise ratio out of the low-pass filter should be about 25 in a typical application.

If the signal-to-noise ratio into the noncoherent detector is greater than unity, there is not much loss in the detection process. Since a signal-to-noise ratio of 25 is typically required at the output of the post-detection integrator, the post-detection integration can achieve a factor of 25 reduction of noise power with reasonable efficiency, which requires a factor of 25 reduction of effective bandwidth.

Without post-detection integration, we must set the quantity $\tau\Delta f$ equal to unity. However, with post-detection integration we can operate with a value of $\tau\Delta f$ of 25 without much loss. Actually, values of $\tau\Delta f$ as high as 100 can be tolerated before serious degradation results. Thus, if the laser receiver bandwidth Δf is set at 10 Mc, the pulse width τ can be as large as 10 μsec before serious loss results ($\tau\Delta f=100$). However, we would prefer that τ be reduced to about 1 μsec ($\tau\Delta f=10$).

C. *Effect of Coherent Detection in Photodetector*

Section IV derives in (56) the signal-to-noise ratio achieved with coherent detection in a photodetector to be as follows:

$$\frac{P_{so}}{P_{no}}=\frac{QP_s}{[h\nu[1+(P_n/P_r)+(\beta T_{\mathrm{amp}}/RGP_r)]+Q\sum p_n]\Delta f}, \tag{33}$$

where

$$\beta = Kh\nu/Qe^2. \tag{34}$$

P_{so}/P_{no} = signal-to-noise power ratio at output of receiver
Δf = noise bandwidth of receiver
P_s = received signal power into photodetector
Q = quantum efficiency of photodetector (electrons per photon)
$h\nu$ = energy per photon = Planck's constant h times optical frequency ν
K = Boltzman's constant
e = charge of electron
P_n = optical noise power into photodetector
P_r = power in useful spectral line of local oscillator signal
$\sum p_n$ = sum of the densities of optical noise spectra separated from the local oscillator frequency by the frequency of the pre-detection filter.
T_{amp} = effective noise temperature of amplifier that follows photomixer
R = equivalent noise resistance of amplifier which follows photosurface
G = noiseless gain between photosurface and amplifier.

$$P_n = P_d + P_b + P_{rn} \tag{35}$$

where

P_d = equivalent power of dark current photodetector
P_b = background radiation power
P_{rn} = noise power in local oscillator reference.

The equivalent power in the dark current is related to the dark current by

$$P_d = (h\nu/Qe)I_d \tag{36}$$

where

e = change of electron
I_d = dark current of photodetector.

The optical noise power density for an IF frequency f_i is

$$\sum p_n(f_i) = p_{rn}(\nu_r - f_i) + p_{rn}(\nu_r + f_i) + p_{bn}(\nu_r - f_i) + p_{bn}(\nu_r + f_i) \tag{37}$$

where

f_i = IF frequency
ν_r = local oscillator reference frequency
p_{rn} = power density of noise sideband of local oscillator reference
p_{bn} = power density of background radiation.

It was shown previously that the noise power density of a photoreceiver is ideally equal to $h\nu$. However (33) shows in the denominator three terms which increase the noise above this value. These terms are as follows:

1) *Excess shot noise* $(P_n/P_r)h\nu$*:* The higher the incident optical power on the photosurface the greater is the shot noise. If the local-oscillator reference P_r were the only significant optical power, the shot noise would be a minimum and would give an equivalent noise power density of $h\nu$ in the coherent detection. The power P_n represents optical noise, the local-oscillator signal, dark current (which is equivalent to an incident optical power), and background optical radiation. This power P_n increases the shot noise above the minimum value. To keep this excess power relatively small, the local-oscillator reference power P_r should be large in comparison to the effective noise power P_n.
2) *Amplifier Noise* $(\beta T_{\mathrm{amp}}/RGP_r)h\nu$*:* This term depends upon the noise of the amplifier that follows the photosurface and the means of coupling the signal to the amplifier. The higher the local-oscillator power P_r the smaller this term is. For photomultiplier tubes this term is negligible. For presently available TWT photomixers the term is greater than $h\nu$, but with advanced designs it is expected that this can be remedied.

3) *Local-Oscillator and Background Noise Density* $\sum p_n$: These terms are due to coherent beats of the local-oscillator reference with the background radiation and the noise skirts of the local-oscillator signal. It appears that the contribution due to background radiation is small, but the contribution due to local-oscillator noise may be significant. Note that the higher the local-oscillator signal the larger this term is.

There is also another more complicated noise term that was not considered, which is due to beats between components of the background noise. If the background power is small in comparison to the local-oscillator power, this noise is small.

It should be noted that the excess noise terms 1) and 2) are inversely proportional to local-oscillator power, whereas the contribution in the noise term 3) due to local-oscillator noise is directly proportional to local-oscillator power. Thus there is an optimum value of local-oscillator reference power than will minimize the sum of these terms. It is hoped that by appropriate design this minimum can be kept small with respect to $h\nu$.

IV. Photoelectric Mixing

Coherent optical detection can be achieved by beating the incoming coherent optical signal with a strong coherent local oscillator and allowing the resultant signal to fall upon a photoelectric surface. In this section the signal analysis, noise sources and signal-to-noise ratio are first discussed. It is shown that with coherent detection the detectivity can be limited only by the quantum efficiency of the detector if extraneous beats from the local oscillator and noise sources are negligible.

Two practical photodetectors are then evaluated relative to their performance in coherent optical mixing. The photomultiplier tube can provide high sensitivity, but appears to be limited to a bandwidth of 300 Mc (although wider bandwidths appear to be possible).[1] Microwave phototubes which are still in the developmental stage can provide wider bandwidths, but up to now are of low sensitivity.

A. *Signal Analysis of Mixing Process*

The photocurrent output from a photoemissive surface is proportional to the input power. If two waves of amplitudes proportional to $\sqrt{P_s}$ and $\sqrt{P_r}$ and angular frequencies ω_s and ω_r are allowed to beat together, the square of the resultant instantaneous amplitude determines the instantaneous photocurrent.

The two waves may be considered as two rotating vectors with an angular difference of $(\omega_s - \omega_r)t$ where t is time. The square of the resultant is found by adding the two waves vectorially and squaring. It is

$$P_o = P_s + P_r + 2\sqrt{P_s P_r}\cos(\omega_s - \omega_r)t. \tag{38}$$

The ratio between the output photocurrent and the input power to a photoemissive surface is the responsivity ρ. Thus

$$I_o = \rho P_o \tag{39}$$

where I_s is the signal photocurrent in amperes. The responsivity is related to the responsive quantum efficiency Q by

$$\rho = \frac{Qe}{h\nu} \tag{40}$$

where e is the electronic charge and $h\nu$ is the energy per photon. Substituting (38) for P_s in (39) gives the output current

$$I_o = \rho[P_s + P_r + 2\sqrt{P_s P_r}\cos(\omega_s - \omega_r)t]. \tag{41}$$

The ac component of the current is $2\rho\sqrt{P_s P_r}\cos(\omega_s - \omega_r)t$, which is the output current at the beat frequency. The mean square value of this ac current is

$$i_s^2 = 2\rho^2 P_s P_r. \tag{42}$$

In the case of a superheterodyne receiver, the powers P_s and P_r represent the received signal and the local-oscillator reference. The received signal is collected by an optical antenna, which could be a mirror or lens, and is added to the local-oscillator power before it is incident on the detector.

B. *Noise Considerations*

Random Noise: The principal random noises present in the output current of a photoemissive diode are the shot noise of the dark current and the photon noise due to the incoming radiation signals. Both noises are observed in the output current of the photoemissive surface and are indistinguishable if the photon arrival is random. Shot noise is due to the fluctuations in the temperature-limited thermionic emission process and its magnitude is determined by the cathode material, area and temperature. Photon noise is defined as the noise in the output current due to fluctuations in the rate by which radiation quanta acts on the photocathode. It is the net effect of the fluctuations in both the incident power and emitted electrons.

At frequencies less than the reciprocal of the transit time, the noise spectrum of the dark current shot noise, $\omega_d(f)$, is[2]

$$\omega_d(f) = 2eI_d \tag{43}$$

[1] G. A. Morton, R. M. Matheson, and M. H. Greenblatt, "Design of photomultipliers for the sub-millimicrosecond region," IRE Trans. on Nuclear Science, vol. NS-5, pp. 98–104; December, 1958.

[2] V. K. Zworykin and E. G. Ramberg, "Photoelectricity," John Wiley and Sons, Inc., New York, N. Y., p. 251; 1949.

where e is the ele[...] rent. The mean square noise current i_d^2 is

$$i_d^2 = \omega_d(f)\Delta f = 2eI_d\Delta f \tag{44}$$

where Δf is the receiver noise bandwidth.

When the quantum efficiency is small compared to unity, the random fluctuations in incident background radiation are negligible compared to those of the photoelectric emission process.[2] From Table I it can be seen that the quantum efficiencies of typical photosurfaces satisfy this criteria.

TABLE I

CHARACTERISTICS OF PHOTOSURFACES AT LASER WAVELENGTHS

Type	Laser Wavelength Å	Dark Current (ampere/cm²)	Noise Equivalent Current (ampere/cm²)	Equivalent Noise Power Input* (w)	Quantum Efficiency	Responsitivity (ampere/w)
S-20	6943	1×10^{-16}	5.7×10^{-17}	4.4×10^{-15}	4×10^{-2}	1.3×10^{-2}
S-1	11,500	1.6×10^{-10}	7.2×10^{-15}	7.2×10^{-11}	1.5×10^{-4}	1×10^{-4}

* Power required to produce a signal-to-noise ratio of unity in a 1-cps bandwidth and a cathode area of 1 cm² at indicated wavelength.

The randomness of photoelectric emission is the same as those of thermionic emission and thus the mean square noise current i_b^2 due to background is

$$i_b^2 = 2eI_b\Delta f \tag{45}$$

where I_b is the average photocurrent due to background radiation.

Photoelectric emission I_c due to coherent local oscillator or signal radiation will also have random fluctuations. The mean square noise currents due to signal and local oscillator are

$$i_c^2 = i_r^2 + i_s^2 = 2e(I_r + I_s)\Delta f. \tag{46}$$

Dark Current: The dark current is the thermionic emission of the photocathode. The total current is a function of the cathode area, work function and cathode temperature. If the cathode is cooled to 0°K and there is no background, the detectivity of the detector will be restricted only by the quantum efficiency no matter whether the detection is coherent or noncoherent.

The two most useful photoemissive surfaces for present laser technology are the S-20 and S-1 surfaces. Table I summarizes their characteristics. Also given in this Table is the quantum efficiency and responsitivity data at the above wavelengths. The data has been obtained from data assembled by Jones[3] and Sharpe.[4]

Radiation Background: When looking into space, noncoherent radiation from the sun, moon, planets and [...]ated[3] that the total radiation from the entire sky on the earth is 10^{-10} w/cm². The total solar radiation on the earth[3] is 0.13 w/cm² and the reflected radiation from the moon[4] is approximately 10^6 times less. Reflected sunlight from other sources during daylight hours will also be present.

The amount of radiation effective, at typical laser wavelengths, upon a photomixer may be calculated if the approximate blackbody temperature of the source is known. The result of this calculation is shown in Table II. It was assumed that the radiation sources had a 6000°K blackbody temperature and that a filter 10 Å wide was used in front of the detector. (The sun approximates a 6000°K blackbody and multilayer interference filters can be made with bandwidths of approximately 10 Å. Thus, this estimate can be considered representative in the background level that might be encountered in a typical receiver system.)

TABLE II

APPROXIMATE BACKGROUND POWER DENSITY

Source \ Wavelength	Power Density in 10 Å Wavelength Interval at Indicated Wavelength 6943 Å	11,500 Å
Sun	1.3×10^{-4} w/cm²	5.2×10^{-5} w/cm²
Moon (Reflected Sunlight)	1.3×10^{-10} w/cm²	5.2×10^{-11} w/cm²
Space (Starlight)	1×10^{-13} w/cm²	4×10^{-14} w/cm²
Good Diffuse Reflector in Sunlight	3×10^{-5} w/cm²-ster	1.2×10^{-5} w/cm²-ster

The values of Table II must be multiplied by the effective collecting area of the optics to determine the power incident on the detector.

Solar reflections from clouds, water or other earthly objects are sources of intense daytime backgrounds. If the reflection is specula, the radiation is equivalent to direct solar radiation. From diffuse sources such as clouds, land, etc., the amount depends on the scattering coefficient and the solid angle subtended by the object at the receiver.

If the background object is a perfectly diffuse reflector, a simple expression may be written to describe the flux effective on the receiver's detector. When a dif-

[3] J. H. Shaw, "The radiation environment of interplanetary space," *Appl. Optics*, vol. 1, pp. 87–95; March, 1962.

[4] F. W. Sears, "Optics," Addison Wesley Publishing Co., Reading, Mass., p. 337; 1958.

fuse surface is ... emittance M is[5]

$$M = \frac{BL}{\pi} \tag{47}$$

where B is the diffuse reflection coefficient. The flux incident on the detector is $M\Omega A_o$ where Ω is the effective solid angle of background subtended by the detector and A_o is the collecting area of the optics. The background power P_b acting on the detector photosurface is then

$$P_b = \frac{BL\Omega A_o}{\pi}. \tag{48}$$

Clouds, snow and ground can present a high background level to the receiver. The diffuse reflectance of some natural terrain objects has been reported[6] to vary from 0.02 to 0.74. Clouds also will have a large reflection coefficient. The objects viewed will vary with angle of illumination and wavelength. During the daytime the sun is the illuminant. Table II gives the brightness for $B=0.74$. This corresponds to the reflectance of a salt bed but is also approximately typical of the reflection from snow, clouds or any highly reflecting white surface.

Local-Oscillator Noise: The output of the local oscillator can contain coherent and noncoherent components which are not useful in the mixing process. Both will produce random noise in the photocurrent. The coherent radiation will consist of sidebands of the local oscillator frequency. Sidebands are caused by multimoding or modulation of the laser. By keeping the lasering excitation near threshold, multimoding can be minimized. Recent measurements[7] have shown the half-power width to be of the order of a few cps near threshold. Modulation sidebands will be generated if the local oscillator is modulated. Neither of these represents useful output and are sources of noise.

Noncoherent radiation can originate from spontaneous emission of the lasering medium or the output from a pumping source. Radiation at frequencies distant from the laser frequency can be eliminated by using optical filters. Multilayer narrow band-pass interference filters have at best a width at the half-power points of 5 to 10 Å. Hence they will still pass the spontaneous radiation present around the lasering frequency.

The direction of spontaneous emission from an atom is random. The net result of many atoms emitting is a spherically propagating radiation. In contrast to this the coherent radiation from present lasers propagates unidirectionally. Thus a reduction in the ratio of noncoherent to coherent output can be accomplished by restricting the laser output to a small solid angle.

Other Noise Sources: The signal power output coupled from the photomixing device should be greater than the noise power of succeeding amplifiers or RF mixers. If coupling is inefficient, considerable signal power may be lost. Thus it may be desirable to have some form of gain between the photocathode and the output coupling. The commonly used method is secondary emission multiplication. However, this can increase the noise level observed in the photocurrent. The noise increase is due to the statistical nature of secondary emission multipliers, and has been observed[8] to be of the order of 15 per cent.

Coherent Noise Source: Eq. (42) shows that the higher the local-oscillator power the greater is the output signal level from the photodetector. However, the local oscillator can have sidebands, although small, which lie at or near the signal frequency and are in the bandpass of the system. Thus, as the local oscillator is increased in power, a signal-like noise composed of mixed local-oscillator products can override the signal to be detected. Heterodyning of the local oscillator with background can also produce other extraneous beats which could limit sensitivity. However, these beats will be negligible for noncoherent background.

The total mean square current due to these mixed products is the sum of the individual mean square values lying in the bandwidth of the receiver

$$i^2_{\text{mixed}} = \sum_{\Delta f} i_n^2. \tag{49}$$

The values of the beats can be determined from (49) providing the power distribution of the local oscillator and the background is known. If the local oscillator is symmetrical and the summing is performed over both upper and lower sideband the sum of the beats is from (42)

$$i^2_{\text{mixed}} = 4\rho^2 P_r \sum p_n \Delta f \tag{50}$$

where p_n is the power density spectrum of the local oscillator sidebands and background.

C. *Signal-To-Noise Ratio*

The mean signal-power-to-noise-power ratio of the photocurrent, which is the amplifier input, is

$$\frac{P_{si}}{P_{ni}} = \frac{i_s^2}{i_d^2 + i_b^2 + i_c^2 + i_{nr}^2 + i^2_{\text{mixed}}}. \tag{51}$$

Define an equivalent optical noise power P_n as

$$P_n = \left(\frac{I_d}{\rho}\right) + P_b + P_s + P_{nr}. \tag{52}$$

[5] Sears, *ibid.*, see p. 339.

[6] E. V. Ashburn and R. G. Weldon, "Spectral diffuse reflectance of desert surfaces," *J. Opt. Soc. Am.*, vol. 56, pp. 583–586; August, 1956.

[7] A. Javan, *et al.*, "Frequency characteristics of a continuous-wave He-Ne optical maser," *J. Opt. Soc. Am.*, vol. 52, p. 96; January, 1962.

[8] J. Sharpe, "Photoelectric cells and photomultiplier," *Electronic Tech.;* June, 1961.

Substituting the expressions in Table III into (51) gives

$$\frac{P_{si}}{P_{ni}} = \frac{2\rho^2 P_s P_r}{[2e(P_n + P_r) + 4\rho^2 P_r \sum p_n]\Delta f} \tag{53}$$

for the signal-to-noise ratio in the photocurrent.

TABLE III
SUMMARY OF MEAN SQUARE NOISE EXPRESSIONS

Noise Source	Noise Expression
Dark current	$i_d^2 = 2eI_d\Delta f$
Noncoherent background including spontaneous radiation	$i_b^2 = 2e\rho P_b \Delta f$
Signal and useful local oscillator radiation	$i_c^2 = 2e\rho(P_s + P_r)\Delta f$
Local-oscillator shot noise due to sidebands	$i_{nr}^2 = 2e\rho P_{nr}\Delta f$
Local-oscillator self and background beats in bandwidth Δf	$i^2_{\text{mixed}} = 4\rho^2 P_r \sum p_n \Delta f$

The photosurface may be followed by virtually noiseless secondary emission amplification which is in turn followed by a conventional amplifier. The signal-to-noise power ratio P_{so}/P_{no} at the amplifier output is

$$\frac{P_{so}}{P_{no}} = \frac{2\rho^2 P_s P_r}{\Delta f[2e\rho(P_n + P_r) + 4\rho^2 P_r \sum p_n + FKT/RG]} \tag{54}$$

where R is the equivalent noise resistance of the amplifier, F is the noise figure, and G is the gain of the secondary emission multipliers. Simplification of (54) yields the expression

$$\frac{P_{so}}{P_{no}} = \frac{\rho P_s}{\Delta f\left[e\left(1 + \frac{P_n}{P_r}\right) + \frac{FkT}{2RG\rho P_r} + 2\rho \sum p_n\right]}. \tag{55}$$

Expressing ρ in terms of quantum efficiency gives for (55)

$$\frac{P_{so}}{P_{no}} = \frac{QP_s}{h\nu\Delta f\left[1 + \frac{P_n}{P_r} + \left[\frac{FkTh\nu}{2RGQe^2}\right]\frac{1}{P_r} + 2Q\sum p_n\right]}. \tag{56}$$

Monochromatic Local Oscillator: If the local oscillator does not have significant sidebands, the ideal detection situation can be approached by making the local oscillator power large compared to random noise power. Assume

$$P_r \gg P_n, \tag{57}$$

$$P_r \gg \frac{FkTh\nu}{2RQGe^2}, \tag{58}$$

$$p_n = 0. \tag{59}$$

The signal-to-noise ratio becomes

$$\frac{P_{so}}{P_{no}} = \frac{QP_s}{h\nu\Delta f}. \tag{60}$$

Thus, to achieve the best detectability, the quantum efficiency of the detector should be as large as possible. However, Table I shows that the quantum efficiency of present photoemissive surfaces is small and that the ideal detection case cannot now be approached.

Noise Figure: The term $h\nu\Delta f$ in (60) is the optical frequency equivalent of the usual $kT\Delta f$ encountered at lower frequencies and represents the lower limit of noise power. Thus, $h\nu\Delta f$ is the noise figure reference level for optical frequency operation. This reference level is derivable from the quantum mechanical expression for noise power density which is[9]

$$\omega(\nu) = \frac{h\nu}{\exp\left(\frac{h\nu}{kT}\right) - 1} + h\nu. \tag{61}$$

At optical frequencies, $h\nu \gg kT$, and (61) becomes approximately

$$\omega(\nu) \cong h\nu. \tag{62}$$

In contrast, at microwave frequencies and below, $kT \gg h\nu$ and (61) approximates kT:

Local-Oscillator Power: The true local-oscillator frequency distribution is not clearly known at present. Consequently statements about setting the local-oscillator power can not be made with certainty.

However, if the local oscillator is monochromatic its output power can be set much larger than the equivalent background power P_n to reduce the effect of random noise on sensitivity. The available local oscillators, such as the helium neon laser, have output power levels of 1 to 10 mw. From Table I it can be seen that the equivalent dark current power is small relative to a milliwatt.

The radiation density from background will be integrated by the optics. From Table II it is evident that even if the collecting area is as large as several square meters, star and moon background levels will be much less than a milliwatt. However, direct solar background will be severe and detection of the small signals will be limited against the sun. Daytime operation will depend upon the individual circumstances encountered. If operation is against a source surrounded by bright clouds, diffuse reflections the background level may be excessively high and the field of view would have to be narrowed to improve sensitivity.

If standard photomultipliers are used for mixing, a limit is placed upon local oscillator strength and back-

[9] B. M. Oliver, "Some potentialities of optical masers," Proc. IRE, vol. 50, pp. 135–141; February, 1962.

ground levels by fatigue and burnout effects in the multipliers due to overloading. Desirable levels will be considerably less than a milliwatt and are given later for two different phototubes.

Local-Oscillator Beats: If the local oscillator is not monochromatic or has significant sideband components, the local oscillator power cannot be raised indiscriminately, for, as the local-oscillator power is increased, the beat components increase also. The local-oscillator sideband requirements can be derived from the denominator of (55) by requiring that the random noise components be greater than the selfbeats. Neglecting amplifier noise, we have

$$2Q\sum p_n \ll h\nu\Delta f\left[1+\frac{P_n}{P_r}\right]. \quad (63)$$

If $Pr \gg P_n$ this becomes

$$\sum p_n \ll \frac{h\nu\Delta f}{2Q}. \quad (64)$$

Comparison of Coherent Detection with Noncoherent Detection: The advantage of coherent detection over noncoherent detection is greater sensitivity in the presence of random noise. To compare them, the signal-to-noise ratios for noncoherent detection must be written. Neglecting amplifier noise the signal-to-noise power ratio at the output of a noncoherent detector is from (39) and Table III

$$\frac{P_{so}}{P_{no}} = \frac{\rho^2 P^2_{s(nc)}}{2e\Delta f[I_d + \rho P_b + \rho P_{s(nc)}]} \quad (65)$$

where $P_{s(nc)}$ is the noncoherent radiation signal power.

Using the definition of the equivalent noise power given by (52) when P_{nr} is zero, (65) may be expressed as

$$\left[\frac{P_{so}}{P_{no}}\right]_{nc} = \frac{\rho P^2_{s(nc)}}{2e\Delta f P_n}. \quad (66)$$

The signal-to-noise for coherent detection with a large monochromatic local oscillator and negligible self beats is from (60)

$$\left(\frac{P_{so}}{P_{no}}\right)_c = \frac{\rho P_{s(c)}}{e\Delta f}. \quad (67)$$

A comparison of the coherent and noncoherent cases may be made by setting the signal-to-noise ratios equal to each other and solving for $P_{s(nc)}$. The result is given by

$$P_{s(nc)} = \sqrt{2P_n P_{s(c)}}. \quad (68)$$

Noncoherent detection capability will approach coherent detection in two different situations: the case of large signal, and the case of zero background with a cooled detector.

Large Signal: When the signal power is large compared to the background power and dark current equivalent power (65) becomes

$$\frac{P_{so}}{P_{no}} = \frac{\rho P_{s(nc)}}{2e\Delta f} \quad (69)$$

and the relationship between the coherent and noncoherent case

$$P_{s(nc)} = 2P_{s(c)}. \quad (70)$$

Zero Background: If there is no background the residual limiting noise is due to dark current. By cooling the photosurface the thermionic current is reduced ideally at 0°K, to $I_d=0$. Then signal noise again limits detection and (69) and (70) apply to this case.

D. Photoemissive Detectors

Photomultipliers: High-speed photomultipliers are usable as wide-band photomixing devices. These tubes contain a photoemissive surface and several stages of electron multiplication. The response time is limited by a time spread introduced in the signal pulse by the electron multipliers. The spread is due to a variation in transit time of electrons between the photoemissive surface and the collector. The photomultiplier anode is connected in series with a load resistor at the input of an amplifier following the tube. The equivalent circuit is a constant current generator driving the load resistor and shunt capacity. Excluding the fundamental transit-time spread of the multipliers, the tube response can be limited by the time constant of the output circuit.

For efficient operation, the noise due to the photomultiplier should be greater than or equal to the noise figure of the amplifier. If G^2N is the mean square noise current of the multiplier output, and $FkT\Delta f$ is the amplifier noise power, then

$$G^2NR \geq FkT\Delta f \quad (71)$$

where R is the load resistor and G the multiplier gain. From the noise summary of Table III,

$$N = 2e\Delta f[I_D + \rho P_b + \rho P_s + \rho P_r + \rho P_{nr}] \quad (72)$$

if the local-oscillator self beats are negligible. In coherent detection, the local-oscillator power P_r is set to a large value, satisfying the inequality

$$P_r \gg P_n. \quad (73)$$

Thus, (72) reduces to the expression

$$N = 2e\Delta f\rho P_r. \quad (74)$$

This becomes

$$N = \frac{2e^2 Q\Delta f P_r}{h\nu} \quad (75)$$

when the responsivity is written in terms of the quantum efficiency. Substituting for N in (71) and solving

for R gives the required load resistor value

$$R \geq \frac{(FkT)(h\nu)}{2G^2e^2QP_r}. \tag{76}$$

The high-frequency cutoff f_{hi} is determined by the shunt capacity C across the load resistor. It is

$$f_{hi} = \frac{1}{2\pi RC}. \tag{77}$$

Substituting (76) for R in (77) gives

$$f_{hi} = \frac{G^2e^2QP_r}{\pi C(FkT)(h\nu)}. \tag{78}$$

Photomultipliers are commercially available for operation at either the ruby laser or helium neon laser frequencies. The S-20 surface is used in the RCA 7265 and the S-1 surface is used in the RCA 7102 tube. The value of G for the RCA 7102 is 5×10^5 and for the RCA 7265 is 10^7. Because of the large gain, the full power available for a local oscillator cannot be used without causing fatigue in the tubes. The upper power level limit for the RCA 7265 at 6943 Å is about 10^{-8} w, and the saturation level for the RCA 7102 at 11,500 Å is about 2×10^{-5} w.

A calculation of f_{hi} for both cases shows that these tubes, even at the reduced local oscillator power and realistic values of F are not limited in bandwidth by the requirement of (71). Instead they are limited by the time spread due to transit time. The rise time of the high-speed photomultipliers is about 3 nsec. Thus the upper frequency cutoff is of the order of 300 Mc.

Special photomultipliers[1] have been constructed to operate in the submillimicrosecond region. Careful design has reduced the transit time spread. However, these are not generally available.

Microwave Phototubes: The microwave phototube is a new device. Klystrons[10] were originally adapted for the first photomixing experiments; but are narrow-band devices. S-band traveling-wave tubes[11] have been operated as photomixers by illuminating the oxide cathode with laser radiation. At the present time the only microwave phototube available commercially is the Sylvania type SYD 4302. This tube is a modified S-band traveling-wave tube with a photosensitive thermionic cathode.

An experimental S-band photomixer with a semi-transparent photocathode has been designed, constructed and operated at Sylvania's Applied Research Laboratory. A photograph of the tube is shown in Fig. 3. It has a photocathode deposited upon the face plate, appropriate electron optics and an S-band slow-wave helix structure. Tests have been performed on the tube and outputs from a pulsed ruby laser are shown in Fig.

[10] A. T. Forrester, *et al.*, "Photoelectric mixing of uncoherent light," *Phys. Rev.*, vol. 99, pp. 1691–1700; September, 1955.

[11] B. J. McMurty and A. E. Siegman, "Photomixing experiments with a ruby optical maser and a traveling wave microwave phototube," *Appl. Optics*, vol. 1, pp. 51–53; January, 1962.

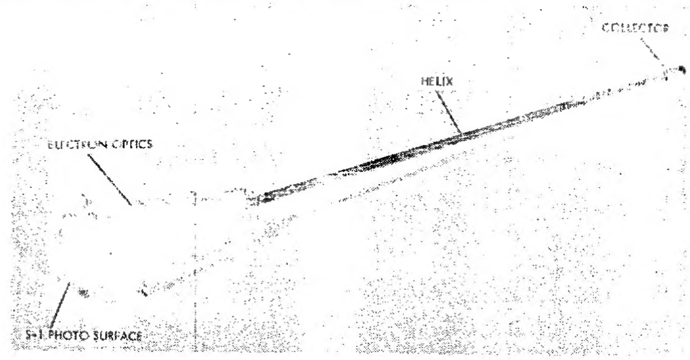

Fig. 3—S-band TWT photomixer.

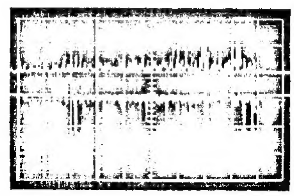

Fig. 4—Signal outputs of photomixer.

4. The RF signals which are beats between laser modes are extracted from the helix by an S-band receiver and the video signals from the collector electrode.

This tube has a sensitivity 10 times greater at 6943 Å than the present oxide cathode type photomixers.[11] With improved processing the sensitivity can be increased by another factor of 500. The mixer is operable over a frequency range of 2 to 4 Gc. A special feature of this tube is its ability to operate as an image dissector and thus provide a capability of scanning an optical field for photoelectric beats. For image dissection the tube must be supplied with a magnetic deflection and focussing system. The helix entrance acts as the dissecting aperture. The deflection and focussing system directs the photoelectrons from elements of the photoelectric optical field through the helix in the scanning sequence.

V. Conclusions

The paper has discussed the various factors that must be considered in the design of a coherent laser radar system. An important requirement to achieve such a system is the development of an efficient laser transmitter having a high-power pulse laser (of less than 10-μsec pulse width) driven by a CW laser oscillator (which supplies the coherent local-oscillator reference). It is expected that such a transmitter will be available in the near future, and coherent laser radar systems will then be practical.

With coherent detection, optical receivers should achieve considerably greater sensitivity during daylight conditions than has been achieved in the past with noncoherent optical detection. The improvement in sensitivity of optical receivers should result in a great many practical applications of optical radar systems.